Fibre Bragg Grating-based Cascaded Acoustic Sensors for Potential Marine Structural Condition Monitoring

Miodrag Vidakovic, Colum McCague, Ioannis Armakolas, Tong Sun, John Carlton and Kenneth T. V. Grattan

***Abstract* – This paper explores the potential of using multiple Fibre Bragg grating (FBG)-based sensors for acoustic emission (AE) detection, thus offering an effective alternative to conventional piezoelectric (PZT) sensors, especially where they have shown limitations in use, such as in the marine sector. A cascaded fibre optic acoustic sensor system, using optical filter signal demodulation has been developed and its performance extensively evaluated. To undertake this under standardized conditions, the optical sensor system was evaluated using a glass plate to detect the acoustic signal, followed by an evaluation using a metal plate to identify the location of acoustic sources, when subjected to sonotrode excitation, mimicking acoustic detection in cavitation detection. Under these circumstances, a very good agreement has been reached between the outputs of the optical acoustic sensors and of the co-located PZT acoustic sensors. This work confirms the utility of these sensors – they can detect not only weak AE signals, but also enable multipoint simultaneous measurement, showing their potential for condition monitoring applications, especially in the marine sector.**

***Index Terms*—Fibre Bragg Grating (FBG), acoustic emission, piezoelectric (PZT), cavitation, structural health monitoring**

I. INTRODUCTION

In the marine industry, cavitation erosion has posed a key technical challenge to a variety of marine structures. A series of phenomena is considered to be the cause of cavitation erosion, which cause multi-million dollar damage to marine structures across the world annually. Effects such as bubble collapse and rebound, micro-jet formation and clouds of collapsing micro bubbles and cavitation vortices [1] do occur and cause the build-up of damage. Recent studies have suggested that a very high proportion of the collapse energy of a large cavity is then focused into a small region of the solid surface, which accordingly causes the erosion [2] and damage seen. In addition to problems from large cavities, the power created by the collapse of micro-cavities results in shock waves which cause the erosion of the solid material [3] from which marine structures are made. The initiation of erosion produces acoustic waves – these are high frequency waves which are believed related to crack formation and which propagate inside the vulnerable materials used [2]. In order to prevent the erosion seen, accurate acoustic emission detection is of real importance. An analysis of the AE signals captured therefore can be of real value in the identification of cavitation erosion signatures and thus the prevention of the erosion seen.

Piezoelectric (PZT) sensors have been widely used for this purpose as they are relatively inexpensive, highly sensitive and can measure signals with a broad bandwidth [4]. However, as electrically-based sensors, they have shown certain limitations when used for tests underwater and also when multiple sensors are required to be deployed simultaneously, as multiplexing large numbers of such sensors is cumbersome.

The first acoustic systems based on fibre optic technology were reported in 1977 by Bucaro *et al* [5 -7]. The majority of optical fibre acoustic sensors to date have been based on interferometric configurations such as using Mach-Zahnder [8], Michelson [9], Fabry-Perrot [10] or Sagnac [11] techniques. Recently, distributed feedback (DFB) fibre lasers have been applied to this field (and their use has been reported elsewhere [12]).

Fibre Bragg Grating (FBG)-based methods have previously been reported for AE detection [13]. Compared to conventional PZT ultrasonic sensors, the FBG sensors are of smaller size, showing potential for simultaneous, multi-node measurement using a single connection (multiplexing them on a single fibre). Their immunity to electromagnetic (EM) interference and resistance to the harsh operational conditions that damages many conventional sensors is an advantage, and being optical and not electrically-based, they are ideally suited to operation underwater (including highly conducting sea water).

This paper focuses on the design and implementation of a cascaded FBG-based acoustic sensor system, allowing for multiple points to be measured simultaneously using optical filter demodulation. The ultimate aim is that such sensors could be applied in practical marine applications. To understand better the characteristics of these sensors, they were evaluated under 'standard' and reproducible conditions. Thus a glass plate onto which was dropped a very small but standardized

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mass (a 0.2g steel ball bearing) from a fixed height was monitored using both types of sensors – conventional and optical. This was followed by a series of tests using a metal plate which is also instrumented using both types of sensors and placed in a water tank, with a sonotrode as an excitation source. The aim was to capture, evaluate and compare the signals obtained to determine the location of the acoustic source to simulate the effect of cavitation.

II. FBG-Based Acoustic Sensor Design

The FBGs used as the basis of the sensor devices are 'inscribed' into a photosensitive optical fibre using a high power UV laser [14,15] and precision alignment. This process creates a periodic change in the refractive index of the fibre core, thus enabling light to be reflected at a particular wavelength, λ_B, (which then can readily be monitored). The governing equation is shown as (1) where n_{eff} is the effective refractive index of the fibre core and Λ is the periodic spacing of the grating:

$$\lambda_B = 2\, n_{eff} \Lambda \tag{1}$$

The principle of operation of the FBG-based sensor system is based on monitoring the wavelength shift of one or more of these reflected signal, each at a specific wavelength, and modulated by the measurand, (strain or temperature changes applied to the FBG are frequently monitored this way.)

The detection of acoustic emission (AE) is thus analogous to the measurement of dynamic strain, albeit at much higher frequencies. In order to detect very weak yet high frequency signals, two main interrogation methods have been reported [16,17]. Using the first of these familiar methods, a laser is required and tuned to be centered at a wavelength. The power measured is the power of the laser after it passes through the FBG sensor [18]. The main drawbacks of this technique are high costs and the difficulty in multiplexing. The second and simpler approach is based on optical filter demodulation by passing a narrowband optical signal reflected from the FBG through an optical filter where the intensity of the light signal transmitted through the optical filter varies with the acoustic pressure impinging on the FBG sensor [19, 20]. This latter approach is explored further in this work, both for ease of sensor multiplexing and for the efficient detection of acoustic signals. One issue tackled in this work is to validate the waveforms produced against those from conventional PZT devices (in terms of both shape and arrival time). In addition, capturing the weaker, low-amplitude acoustic signals is challenging – in particular when the familiar bespoke, high frequency interrogation systems are utilized [20].

To tackle this, Fig. 1 shows a typical cascaded FBG-based acoustic sensor system, coupled with a PZT acoustic sensor, co-located with FBG sensor for cross-comparison and allowing the fast capture of the acoustic signals generated.

Fig. 1 illustrates the light signal emitted from a C-Band ASE light source into port 1 of an optical circulator (with a maximum output of 20.9 dBm.) The signal reflected from the cascaded FBGs passes from port 2 to port 3 of the optical circulator. At port 3, a de-multiplexer is used to allow narrow-band signals, each containing a specific FBG signal, to be transmitted through an optical filter array and detected by the photodiode array. This configuration facilitates the capture of high-frequency acoustic signals and the signals obtained are cross-compared with those detected by the PZT sensor, co-located with FBG sensors, as shown in Fig. 1.

III FBG Sensor Characterization

In order to achieve both the required sensing range and high measurement sensitivity, the spectral slope of each band pass filter shown in Fig.1 is required to match with that of a FBG.

Fig.2 shows the typical spectral profile of the narrowband near infrared (NIR) optical filter (labeled BPOF$_1$) and having a full width half maximum (FWHM) of 12 nm and central wavelength of 1548.3 nm.

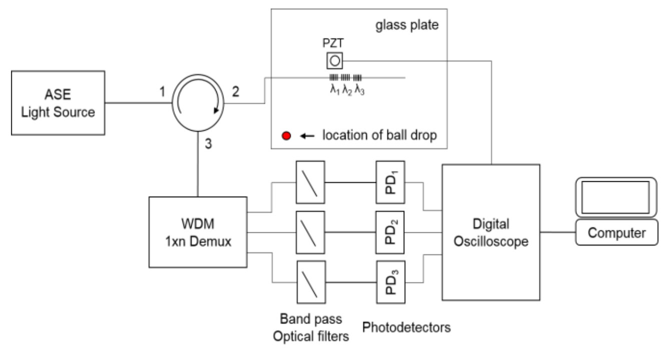

Fig. 1. The experimental setup: the FBG-based cascaded acoustic sensor system, with a co-located PZT acoustic sensor for cross-comparison.

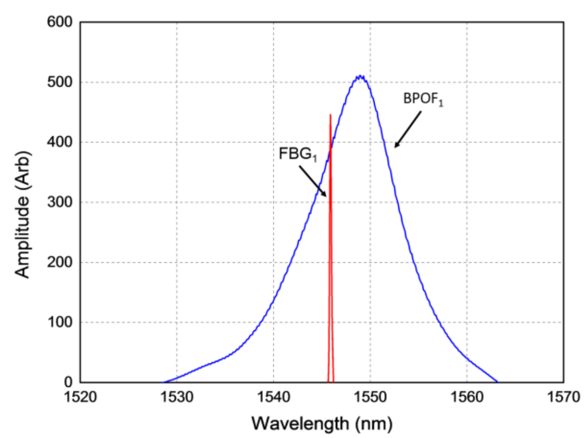

Fig. 2. Spectral slope of the optical filter used in combination with FBG$_1$ optical sensor.

The spectral profile of the first Fibre Bragg Grating (FBG$_1$) (illustrated in Figure 1) is shown in Fig. 2 (labeled FBG$_1$) – the aim is for the centre wavelength of the FBG to lie on the steepest slope of the filter, to offer maximum sensitivity. The same approach applies to the specification of the other filters matching to their corresponding FBGs in the sensor array.

As indicated in Fig.2, FBG$_1$ has a central Bragg wavelength of 1545.8 nm and has been written to have a high reflectivity of about 95%. The typical wavelength/strain sensitivity of a FBG-based sensor is about 1pm/με. Thus the design of the sensors to have the 'match' shown in Fig.2 allows the measurement range to be of approximately 2500 – 2800 με, with a resolution of 8 με.

IV Glass plate tests

A series of tests was conducted using a glass plate as an initial test sample, onto which both FBG and PZT acoustic sensors were bonded using a small amount of cyanoacrylate, creating the pattern shown in Fig.1. Dropping a tiny steel ball was used as an excitation source to create a reproducible acoustic signal – the glass plate was resting on 3 ball bearings. The location of the ball drop is also indicated in Fig.1.

In order to analyze the arrival time and shape of the waveforms in the time domain, the captured waveforms from the 0.3 g ball-drop received from both a FBG and a PZT sensor are shown in Fig. 3.

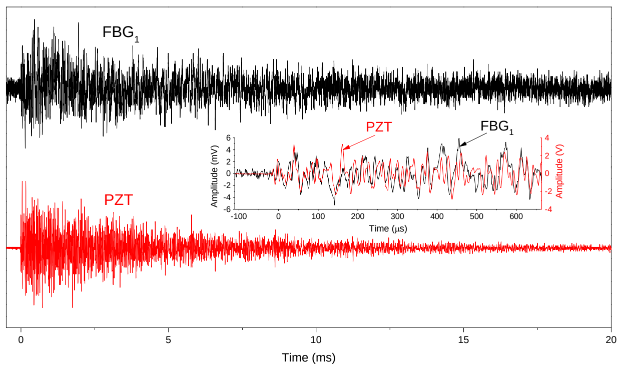

Fig. 3. Time waveforms detected by both FBG based acoustic sensor and PZT based acoustic sensor when glass plate was excited using a steel ball.

Comparing the acoustic signals produced, Fig. 3 shows the close similarity that exists between the waveforms received from both the PZT and FBG devices. The signal arrival times and waveform shapes are evident (as shown in the inset) – giving confidence in that the FBG-based sensor can give signals similar to that seen from the industry-standard PZT sensors. Cyanoacrylate as a bonding agent for the FBG-based sensor to the glass plate was specifically chosen to ensure a 'true' transfer of the acoustic wave profile and achieving the same arrival time of the acoustic signals using both sensors underpins this confidence. Considering the full waveform data for both sensors, it is evident that the level of background noise from the FBG sensor is higher than the PZT sensor. This is an effect caused by the interrogation setup used and may be improved further by using a higher-power optical ASE source or achieving greater reflectivity in the FBG: work is ongoing to improve this.

Using the same experimental setup and method, an investigation of multipoint sensing was carried out using the 3 cascaded FBGs (with a physical interval on the glass plate of 10 mm.) Their optical outputs were connected to the interrogation system (using the same optical filter demodulation scheme illustrated in Fig.2.) It was found that all the FBG sensors responded – showing a similar arrival time and the same waveform shape, when compared to the response of the PZT sensor to FBG_1. The signals received are shown in Fig. 4 – it can be seen that the background noise from the FBG data is higher than that for the PZT sensor. However, the signal to noise ratio (S/N) is satisfactory for a wide variety of acoustic sensing applications, particularly where the pulse arrival time is the most significant parameter (often it is more significant than the waveform shape.) It is interesting to note the effect of the location of the FBG (and the corresponding S/N.) – for example, FBG_1 has the highest S/N (as it is closest to the source), whereas FBG_3 has the lowest. It implies that the further the FBG-based sensor is located from the source, lower the S/N is. However, this demonstration has shown that it is possible to detect the very weak acoustic signal generated from the dropping of a very small ball on a glass plate, using a multi-point FBG sensor array. Further, knowing the speed of sound in solid glass (4540 m/s) and the time needed for the signal to propagate from the source to both FBG_1 and the PZT, it is possible to calculate the distance of the sensors from the source of excitation, which is an important parameter in marine structural condition monitoring.

Data collected show that the time for the first acoustic wave to arrive at the location of FBG_1 is 26.43 μs which compares well to the time measured for the almost co-located PZT, of 27.19 μs. This small time difference in the arrival times arises from their slight spatial mismatch, but shows clearly from the similarity of the data that those two sensors are located very close to each other. It can thus be calculated that the distance from the excitation source to the two sensors is ~120 mm.

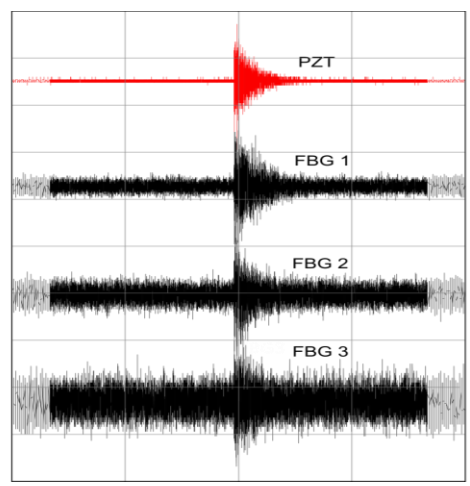

Fig. 4. Comparison of waveforms detected by both the PZT and multi-point FBGs.

VI Metal plate test for Cavitation Monitoring

Moving on from the tests carried out on glass plates, Fig. 5 shows a test-rig set up for the acoustic tests on a metal plate which is placed in a water tank, with an excitation sonotrode mounted 1 mm above. The sonotrode standard frequency is 19.5 kHz. Both the FBG and PZT acoustic sensors were fixed onto the bottom surface of the metal plate using cyanoacrylate.

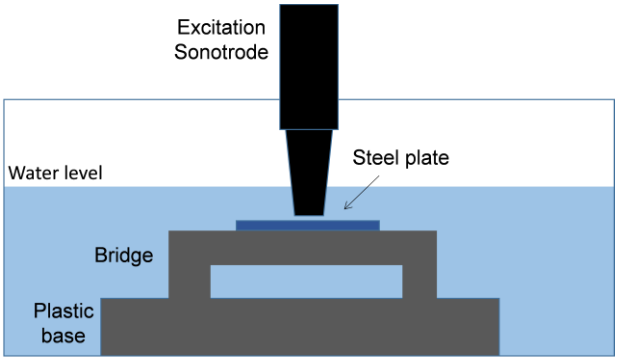

Fig. 5. Schematic of the setup for the acoustic tests of the steel plate instrumented with both FBG and PZT acoustic sensors.

A similar set up to that shown in Fig. 1 is used, with the glass plate substituted for a metal plate and the sonotrode excitation (as illustrated in Fig. 5). The waveforms detected by both the PZT and the co-located FBG sensors, when an excitation sonotrode is operated at a standard frequency of 19.5 kHz, are shown in Fig. 6. This test was repeated several times in order to evaluate the repeatability of the measurements and to ensure that the sensors are reliable and give a reproducible signal.

Fig.7 shows the frequency-domain data obtained from both types of sensors. A Fast Fourier Transform (FFT) algorithm is used to process the time-domain data captured and the output is shown in Fig. 6. It is noticeable that the same frequency element at 19.5 kHz, the excitation frequency from the sonotrode, has been captured by both sensors. The figure shows that the FBG sensor has some additional second harmonic features (which can readily be filtered out) but which are the subject of on-going work.

The results obtained from both the glass plate and metal plate show good agreement between both the optical and the electrical acoustic sensors, giving confidence to the use of the FBG-based sensors in this application. Their ease of being multiplexed has not been exploited in this work, but for marine condition monitoring applications, this shows significant potential.

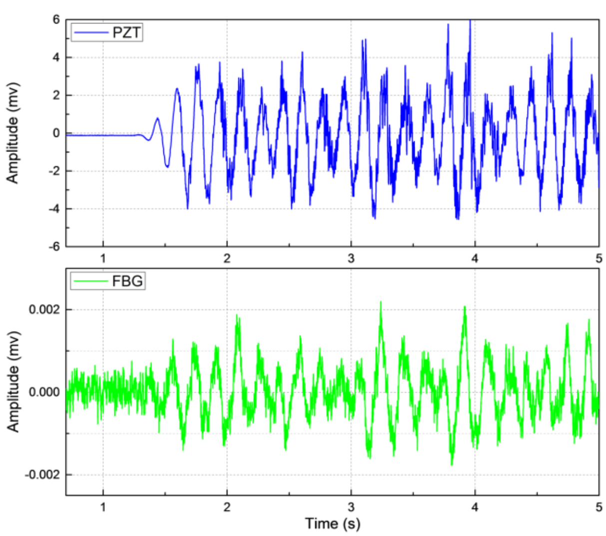

Fig. 6. Acoustic signals acquired by the co-located FBG-based and PZT acoustic sensors when the metal plate is subject to the excitation of the sonotrode at a frequency of 19.5 kHz

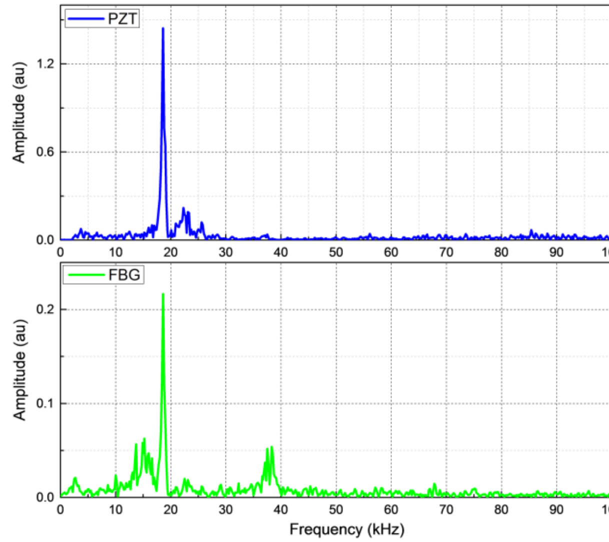

Fig. 7. Frequency response of a FBG-based acoustic sensor and a PZT acoustic sensor illustrating the close match (in this case with a standard sonotrode frequency of 19.5 kHz).

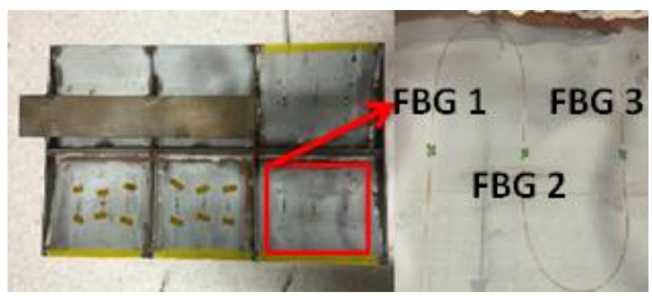

Fig. 8. Inner surface of a rudder mapped with 12 FBGs for acoustic emission monitoring.

DISCUSSION

The research undertaken has shown that the FBG-based sensor evaluated shows a similar satisfactory performance to the industry-standard PZT-based sensors for acoustic monitoring on glass and metal plates. A cascaded FBG-based acoustic sensor system has thus been successfully developed and verified through both the glass plate and metal plate testing, with an aim to find key acoustic signatures. Close cross-comparison between the acoustic signals from both the FBGs and the co-located PZT acoustic sensors has been seen, with similar arrival times and shapes of the detected waveforms. On-going work to enhance the signal-to-noise ratio from the FBG-based sensors is being addressed both by increasing the output power of the optical ASE source used and the reflectivity of each FBG (the reflectivities of the FBGs tested in this work are ~95%).

The research done is directed towards Marine Structural Condition Monitoring and key results for that application include both the familiar PZT type and the new FBG-based sensors detecting the same, known excitation frequency from the sonotrode source. Work is being done to apply these techniques to a commercial marine rudder, provided by our industrial partners. This has been instrumented with 12 cascaded FBGs and a photograph of this instrumented rudder is shown in Fig. 8. An investigation of its characteristics on-going and experimental data from these 12 FBG-based acoustic sensors will be reported in due course. The work carried out to date and reported in this paper gives confidence to that new investigation and ultimately to the use of these sensor arrays in the study of marine cavitation.

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During his carrier as a PhD student, he has been working closely with Industry through the development of a number of optical fibre sensors, underpinned strongly by fundamental photonics, to meet various industrial needs. One of the projects that he has been actively involved in is the development of series of optical fibre sensors integrated into a railway pantograph for its condition monitoring. This is a joint work with Brecknell Willis, Serco and Network Rail in the UK, funded by RSSB (Rail Safety and Standards Board). He is also working together with colleagues from Research Centre of Marine Cavitation from City University London, by developing optical fibre sensor to monitor marine lifting surfaces erosion and cavitation signatures.

Colum McCague received the M.Eng. degree in structural engineering and the Ph.D. degree in civil engineering from Queen's University Belfast in 2009 and 2015 respectively. His Ph.D. research focused on the development of novel cement materials for the encapsulation of nuclear waste containing aluminium. In 2012 he joined the Optical Sensors and Instrumentation Group at City University London where he worked on the development of optical fibre sensors for structural health monitoring. In 2015 he was recruited by the Mineral Products Association, London, as Technical Officer for MPA Cement (formerly British Cement Association). Colum is a member of the Institute of Concrete Technology and works closely with standards organisations in the UK and Europe to develop performance test methods for cement and concrete.

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Tong Sun received the B.Eng. degree, M.S. degree in engineering, and the Ph.D. degrees in engineering for work in mechanical engineering from the Department of Precision Instrumentation, Harbin Institute of Technology, Harbin, China, in 1990, 1993, and 1998, respectively. She also received the Ph.D. degree in applied physics from City University, London, U.K., in 1999.

She was an Assistant Professor at Nanyang Technological University, Singapore, from 2000 to 2001, before she rejoined City University London, in 2001, as a Lecturer. Subsequently, she was promoted to a Senior Lecturer in 2003, a Reader in 2006, and a Professor in 2008 at City University London. She has been leading a research team focused on developing a range of optical fiber sensors for a variety of industrial applications, including structural health monitoring, early fire detection, homeland security, process monitoring, food quality, and automotive emission monitoring, and has been working closely with partners across disciplines from academia and industry, both in the U.K. and overseas. She has authored or coauthored 130 scientific and technical papers.

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John Stephen Carlton Following training as a mechanical engineer and athematician, Professor Carlton served in the Royal Naval Scientific Service undertaking research into underwater vehicle hydrodynamic design and propulsors. Five years later he joined Stone Manganese Marine Ltd as a propeller designer and research engineer. During this time he specialised in controllable pitch propellers and transverse propulsion units but also undertook analysis into other aspects of ship propulsion technology; particularly in the fields of ship powering and manoeuvring. In 1975, he joined Lloyd's Register, first in the Technical Investigation Department and eventually in 2003, became the Global Head of Marine Technology for Lloyd's Register.

After 35 years within Lloyd's Register, Professor Carlton was then invited to become Professor of Marine Engineering at the City University London in which capacity he now serves and is responsible for the postgraduate maritime studies. He is also closely involved with the International Institute for Cavitation Research at the University.

During his career he has presented and published around 120 technical papers and articles on many aspects of marine technology as well as having written a textbook entitled Marine Propellers and Propulsion Professor Carlton has been awarded the Denny Gold Medal of the Institute of Marine Engineering, Science and Technology twice and has also won the Stanley Gray Award for Marine Technology twice. Additionally, he is active in a number of research groups and has sat on several international and government committees. In 2006 he was awarded the degree of Doctor of Science for his contribution to marine technology. Professor Carlton was the 109th President of the Institute of Marine Engineering, Science and Technology in 2011/12 and was elected a Fellow of the Royal Academy of Engineering in 2011. He was also Chairman of the Royal Academy of Engineering's working group on the future propulsion of ships. Professor Carlton in 2014 took over as Director of the Fluids Research Centre at City University London and joined the Technical and Education Committees of the Honourable Company of Master Mariners. He is also a member of The Greenwich Forum.

Kenneth T. V. Grattan received the B.Sc. (Hons.) in physics and the Ph.D. degree in laser physics from the Department of Physics, Queen's University, Belfast, U.K., in 1974 and 1978, respectively, and the D.Sc. degree from City University, London, U.K., in 1992, for his sensor work.

His research involved the use of laser-probe techniques for measurements on potential new laser systems. Following Queen's University, in 1978, he became a Research Fellow at the Imperial College of Science and Technology, London, U.K., sponsored by the Rutherford Laboratory to work on advanced photolytic drivers for novel laser systems. This involved detailed measurements of the characteristics and properties of novel laser species and a range of materials involved in systems calibration. In 1983, he joined City University, London, U.K. as a Lecturer in physics, and was appointed a Professor of Measurement and Instrumentation in 1991, and the Head of the Department of Electrical, Electronic and Information Engineering. The work has been sponsored by a number of organizations including EPSRC, the EU, DERA, private industry and BTG, with whom a joint patent for systems for monitoring in the water industry is held. He has authored or coauthored of more than 500 publications in major international journals and at conferences and is the coeditor (with Prof. B. T. Meggitt) of a five volume topical series on Optical Fiber Sensor Technology. His research interests include the use of fiber optic and optical systems in the measurement of a range of physical and chemical parameters. Prof. Gratton is extensively involved with the work of the professional bodies, having been Chairman of the Science, Education and Technology of the Institution of Electrical Engineers, the Applied Optics Division of the Institute of Physics, and was President of the Institute of Measurement and Control in 2000. He has been Deputy Editor of the Journal Measurement Science and Technology for several years and currently serves on the editorial board of several major journals in his field in the U.S. and Europe. In January 2001, he was appointed Editor of the IMEKO Journal Measurement and also serves on their General Council. He is also the Dean of the School of Informatics.

Prof. Grattan received the Callendar Medal of the Institute of Measurement and Control in 1992, and the Honeywell Prize for work published in the Institute's journal.